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ENERGY MODEL FOR THERMAL ENERGY STORAGE SYSTEM MANAGEMENT INTEGRATION IN DATA CENTRES

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Abstract

In the last years the total energy demand of data centres has experienced a dramatic increase which is expected to continue. This is why data centres industry and researchers are working on implementing energy efficiency measures and integrating renewable energy to overcome energy dependence and to reduce operational costs and CO_2 emissions. The cooling system of these unique infrastructures can account for 40% of the total energy consumption. To reduce the energy consumption, free cooling strategies are used more and more, but so far there has been little research about the potential of thermal energy storage (TES) solutions to match energy demand and energy availability. Hence, this work presents a dynamic energy model able to study the implementation of different energy efficiency strategies and see its effects on the operational conditions, power consumption and ecological footprint. Operational data from a real 125 kW IT data centre located in Barcelona has been used to validate the energy model.

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Keywords: Data centres; thermal energy storage; dynamic model;experimental validation; economic analysis.

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1. Introduction

Here introduce the paper, and put a nomenclature if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.

Data centres which they are facilities used to house computer systems and associated components aim for performance, reliability and security 24 hours a day the 365 days a year, transforming them into a highly energy demand infrastructures. Data centres have traditionally had very controlled environments to increase reliability. In the American society of heating, refrigerating and air-conditioning engineers (ASHRAE) data processing environments thermal guidelines [1], the suitable environmental conditions for electronic equipment are provided. Additionally, Figure 1 shows the temperatures and RH recommended in a psychrometric chart. Besides temperature and humidity, air pollution could also cause failures in data centres. Therefore ASHRAE [2] also provides particulate and gaseous guidelines. In contrast to other types of building, data centres have mostly a constant cooling demand independent of the hour of the day and the season. In the last years the total energy demand of data centres has experienced a dramatic increase which still growing. This is why data centre industry and researchers are undertaking efforts to implement energy efficiency measures and to integrate renewable energy into its portfolio to overcome energy dependence and to reduce operational costs and CO2 emissions. In particular, the cooling system can account up to 40% of the total energy consumption and thus has a great potential for improvement [3]. Moreover, due to the nature of some IT load such as web workload the cooling demand can vary during the day. Thermal energy storage (TES) system can play an important role to match cooling demand and production as well as to reduce operational expenses. Vos [4] showed that for a 300 kW IT facility the energy consumption related to cooling could be reduced by 20% and the energy costs could even be reduced with 35% by shifting the cooling load from day to night. The implementation of a TES system using water as the storage material is taking advantage of the lower ambient air temperature and utilizing the off-peak tariff for electricity. This paper presents a validated dynamic model to predict the consumed power, the operational cost and the ecological footprint depending on management strategies, the integration of TES systems and the data centre location.

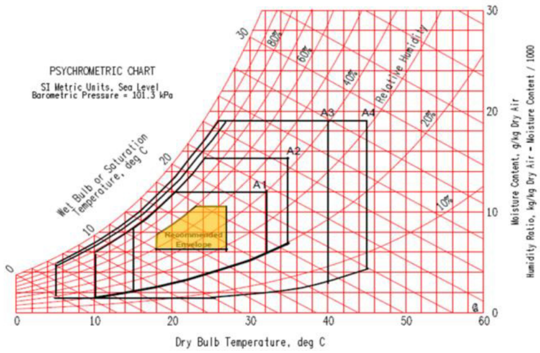

Fig. 1.ASHRAE thermal guides for Data Centre operating environments 0.

2. Methodology

2.1. Data center characteristics

An operative data centre with an IT capacity of 125 kW is used to study the implementation of energy efficiency strategies and to validate the dynamic energy model. The facility was constructed in 2006 and started operations in

2007 for the Universitat Politècnica de Catalunya in Barcelona. It has a TIER II+ level of reliability which means that has redundancy in some of the equipment such as the chillers (N+1) and the PDU (2N). The facility which has an IT room area of 285 m^2 is located in the second basement of a University building and it is surrounded by aisle and other areas by its four sides. This characteristic allows considering the whitespace as insulated from the outside. Figure 2 shows the scheme of the data centre and the equipment distribution. The facility is composed by 70 racks of data and 12 racks of communication equipment. The theoretical maximal power consumption is 4 kW per rack but at the present moment the real average power consumption is between 1.5 and 2 kW per rack. Some racks are distributed in cold/hot aisle containment so recirculation (hot air is mixed with cold air before entering to the IT equipment) is decreased. Notice that some other racks are placed in the whitespace so recirculation and bypass (cold air is mixed with exhaust hot air decreasing its temperature) effect are present.

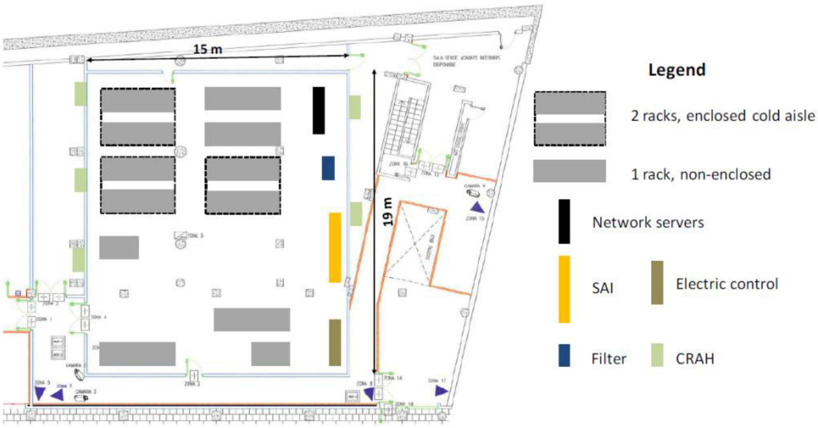

Fig. 2. Data centre layout.

The facility is connected to the public grid. The electricity goes through a transformer before feeding the IT and the cooling equipment. There is also an emergency generator which is connected in parallel to the grid and in case of energy supply failure the switchgear can change the source to the emergency generator. Figure 3 shows schematically the main components of the infrastructure. Notice that all the electrical components are in the whitespace. Therefore the cooling system is also responsible to cool down the heat from the electrical equipment.

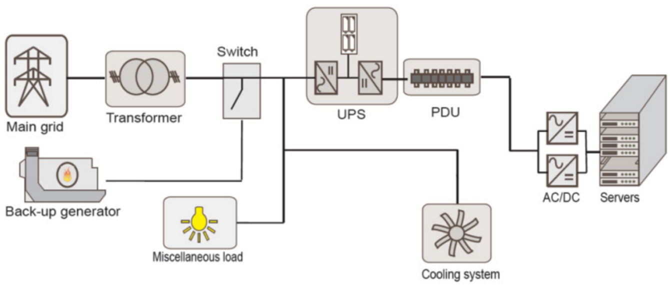

Fig. 3.Scheme of the power supply in the data centre.

The whitespace refrigeration is done using five computer room air handling (CRAH) units which uses chilled water from three water-air chillers. A raised floor is used to distribute the chilled air to the bottom of the racks and the exhaust warm air leaves the room parametrically direct to the CRAHs as it is shown in Figure 2. The 3-way valve of the CRAHs controls the cooling exchange between the chilled water and the exhaust air and it is controlled by the return air (temperature and relative humidity) which is opened or closed depending on the desired working conditions. Each unit keep a constant air flow rate to the IT room of 8500 m^3/h while the total chilled water flow rate is 39.9 m^3/h. There is also a buffer tank of 1 m3 in the supply chilled water to prevent temperature fluctuations. The main characteristics of the cooling equipment are listed in Table 1.

Table 1.Specifications of main equipment.

Chiller	
Model	STULZ 822
Cooling capacity [kW]	77.7
Rated EER	2.6
Water flow rate [m^3/h]	13.3
CRAH	
Model	Uniflair TDCR 1200A
Cooling capacity [kW]	37
Energy consumption [kW]	2.5
Air flow rate [m^3/h]	8500
Water pumps	
Energy consumption [kW]	3
Water flow rate [m^3/h]	42

2.2. Energy model description

The dynamic energy model is based on a component-by-component approach using TraNsient System Simulation program (trnsys). Trnsys, developed by the Solar Energy Laboratory of the University of Wisconsin, is used to simulate the behaviour and to predict the performance of transient thermal systems. Information from the equipment manufacturers, data centre operators and data collected directly in the facility was used to build the energy model. The energy model consists of main system components including chillers (type 655), pumps (type 114), crahs (type 508c), pipes (type 31), etc. which are available in the trnsys library. Those components were connected according to the system configuration already described and shown in Figure 4. The typical meteorological year (TMY2) data was used to obtain the weather conditions in Barcelona. The TMY2 data sets are the typical values of meteorological elements for a one-year period from Meteonorm[5].

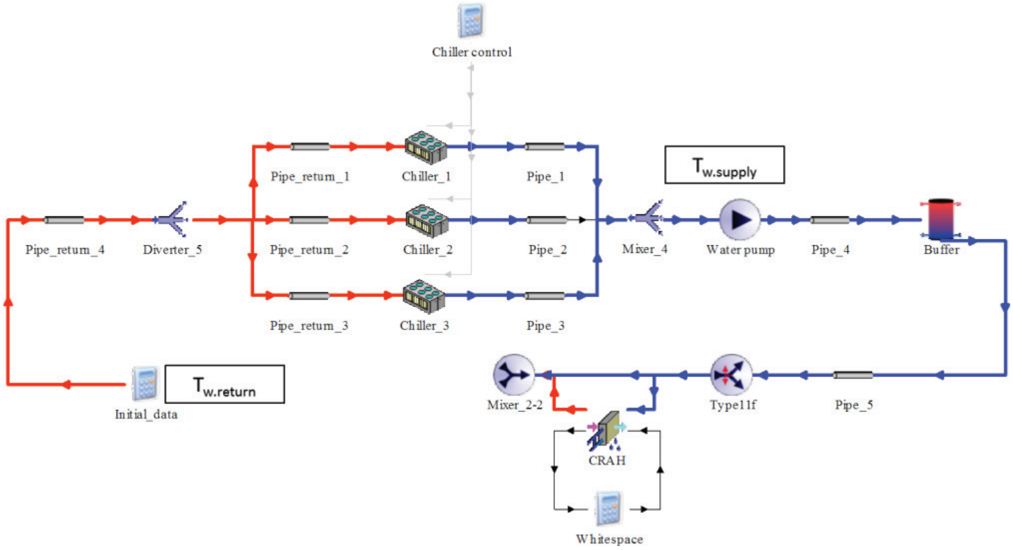

Fig. 4.Scheme diagram of the energy model for the data centre.

3. Results and discussion

3.1. Model validation

For operational data, the water return temperature ($T_{w.return}$) was used as input of the model. The model was validated by comparing the simulation results with the operational data during 12 hours. In the validation, the supply chilled water ($T_{w.supply}$), the return water temperature ($T_{w.return}$), the cooling consumption ($P_{cooling}$) and the total consumption (P_{total}) were selected to validate the model. The actual chiller set points are different between them. Chiller 1 starts when the return water temperature is above 9.5 ºC, when it is higher than 12.5 then chiller 2 also starts and chiller 3 does not start till the return water is above 13.5 ºC. Moreover, the outlet water set point is set at 8ºC. For the CRAH units, the return air temperature set point is set at 25.5 ºC. Figure 5 shows the modelled and the real temperature and power values over a period of 12 hours. According to these results, the predicted values by the model make good agreement with the actual operational data and therefore the consistency of the dynamic model is demonstrated.

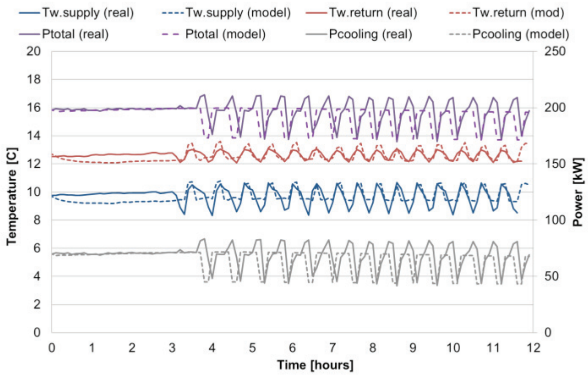

Fig. 5.Temperature and power comparison for model validation.

3.2. TES implementation in data centres

Once the model was validated, it was utilized to study the implementation of TES systems into the data centre portfolio. As described before, the data centre has a redundant chiller which can be used to produce chilled water when its energy efficiency ratio (EER) is higher and/or when the electricity cost is low and store that cold in the TES system. Figure 6 shows the schema of the cooling system at different operational modes. The redundant chiller is used to produce chilled water during the off-peak hours (night) and the cold is stored in the storage tank. During the peak hours (day) the tank is discharged in order to decrease the return water temperature. Notice that in this situation no additional costs are caused for the cold production, and only the costs for the storage by means of the storage material and the infrastructure (storage tank, pumps, etc.) need to be considered. In the present work, water is used as sensible storage material as it is cheap and available in many locations, has the best thermal properties, and possesses good long term stability.

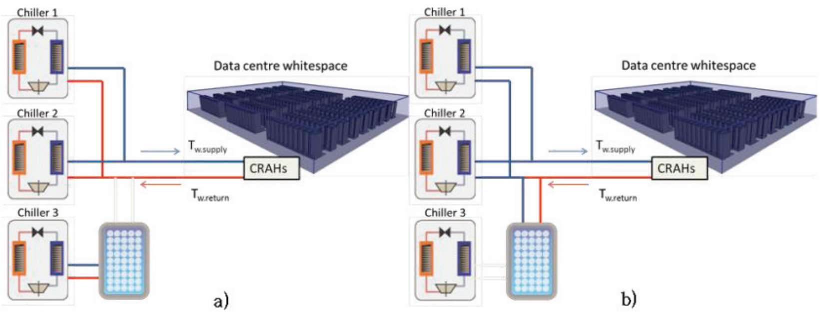

Fig. 6. Schema of the cooling system operating at night (a) and day time (b).

A storage tank of 60 m^3 has been implemented in the cooling system to evaluate the potential of TES system implementation in data centres. An optimization of the storage volumes is needed but it would be done in further studies. Notice that in the actual situation the water flow rate through the CRAHs units has changed being reduced to 26.6 m^3/h. This phenomenon may affect the temperature gradient of the water through the system. Moreover, the chiller 1 and chiller 2 water inlet set points (when they start) were modified to 11.50 and 12.50 ºC, respectively and the chilled water set point has been raised from 6 to 8 ºC. This modification is done to compensate the reduction of chilled water to the whitespace. The results after the implementation of the TES system are compared with a reference case with same boundary conditions.

Figure 7 shows the storage tank temperature and the chillers power consumption. On one hand, in night time period, cooling power increases (the three chillers may be switched on) while the storage tank temperature decreases (charging). On the other hand, in day time and when the electricity price is higher, the overall cooling power decreases while the storage tank temperature increases (discharging). The stored cold is exchanged with the return water and therefore experiences a temperature decreasing before entering both chillers (Figure 8). Once the inlet water is lower than the set point for each chiller (11.50 and 12.50 ºC, respectively) they stop. Notice that the water supply temperature when the TES system is implemented is 2ºC lower than the reference case. This is because all the water is circulating for both chillers while in the reference configuration the water flow rate is divided in the three chillers, increasing its outlet temperature till 10 ºC. This phenomenon would also affect the inlet air temperature to the whitespace. Figure 9 shows the air inlet and return temperatures. As expected in the new scenario the inlet air temperature is lower maintaining the temperature gradient inside the whitespace. Notice that the air inlet temperature to the whitespace is really low and it’s not really recommended. However, the data centre analysed presents high values of bypass and recirculation and therefore in order to avoid hot spots they are working in those inlet ranges. Obviously it would be beneficial for the infrastructure to solve those phenomenon and then working with higher inlet air temperatures.

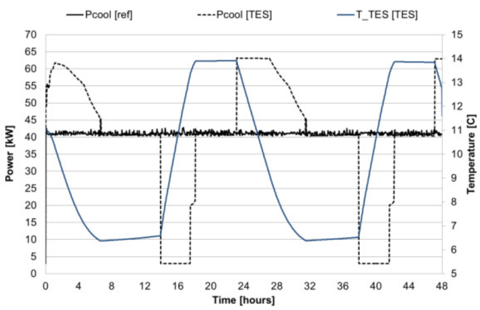

Fig. 7. Storage tank temperature and cooling power consumed.

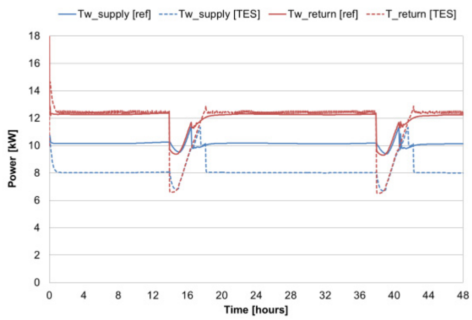

Fig. 8. Supply and return water temperature.

Figure 10 presents the total cooling consumption by means of the cooling production, air management, and TES system for both case studies. The cooling plant energy consumption is almost similar over the time but due to advantage of using the off-peak electricity price the annual electrical costs are quite different.

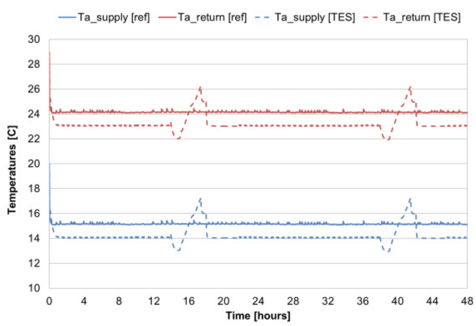

Fig. 9. Inlet and return air temperatures in /from the whitespace.

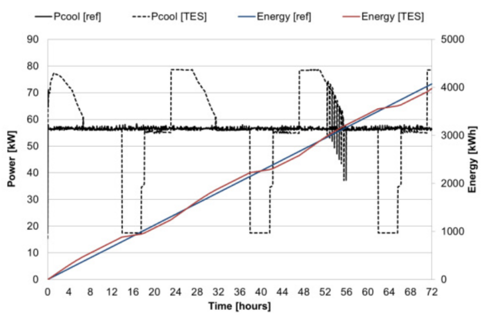

Fig. 10. Power and energy consumption of the cooling system.

To calculate the total cost of the new cooling system, both operational and additional investment costs are taken into account using reference data where the state of art of the technologies for TES systems are presented [6]. Table 5 summarizes the investment costs to implement the different systems and Figure 11 shows the electricity price for final energy use. The exact value for electricity would depend on many factors such as favourable supply contracts (including long-term contracts), discounts for large-scale consumers, different levels of levies and taxes (including exemptions for large-scale consumers), etc. Therefore, the use of this electricity price does not aim to predict the exact final cost but to demonstrate a valuable cost reduction using TES systems.

Table 2: Investment costs for the TES system [6].

TES system	Investment cost
Storage tank and system	$-119.74 \cdot \ln(V_{TES}[m^3]) + 1{,}291.1$ €/m^3
Storage material (water)	2.6 €/m^3

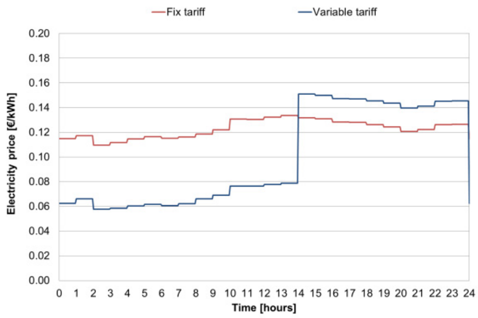

Fig.11. Electricity prices per kWh in Spain.

Both models were also used to see the benefits of using TES in data centres over one year. The implementation of this concept causes slightly more energy consumption when compared to the reference case but the annual electrical cost for the overall facility is lower, being reduced 20%. Figure 12 shows the energy consumption and the annual electrical cost for the overall data centre in both scenarios.

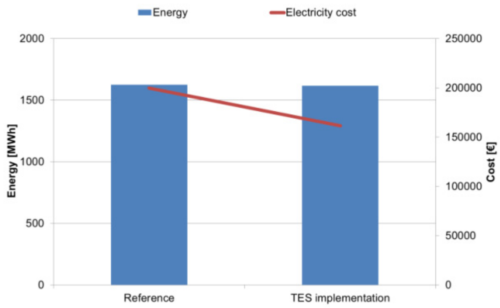

Fig.12.Energy consumption and operational costs.

For the evaluation of the investment the following indicators have been used: Net present value (NPV), discounted payback period and benefit to cost ratio [7]. The NPV represents the net total profit during the life of the project, i.e., the difference between the operational profit and the total amount of expenses. Considering a life time of 10 years, this value reaches almost 250000 €. The discounted payback period represents the period of time required to refund the initial capital plus the interest that could be received from an alternative investment of this capital and is lower than 3 years. Finally the benefit to cost ratio which is defined as the ratio between the total profit and the total cost of the project during its lifecycle (10 years) is 4.22. These economic figures demonstrate the feasibility of the implementation of TES into data centre portfolio.

4. Conclusions

Due to the high growth of IT and Internet over the last years, the electricity and cooling demands of data centres have increased dramatically. To reduce the impact of the energy demand of these unique infrastructures, first energy efficiency strategies and second the implementation of renewable energy are opportunities to be considered. This study evaluates the incorporation of TES systems in the data centre portfolio to take advantage of operating during periords with higher EER and redundant chillers. To do so a dynamic energy model using trnsys was developed and validated with real data from an operative data centre with an IT capacity of 125 kW. The facility which has an IT room area of 285 m2 is located in Barcelona (Spain). A comparison between the operational data and the calculated temperature and power showed a good agreement and therefore proved the consistency of the model proposed. The results show that short term TES is feasible when it is used to store the cold produced by the redundant chiller during off-peak electricity price. The annual electrical cost for the overall data centre facility is being reduced about 20%. The economic figures also demonstrate the feasibility of the implementation of TES strategies into data centres. Considering a life time of 10 years the discounted payback period is lower than 3 years and the benefit to cost ratio after the life time is 4.22.

Acknowledgements

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